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Sanction Effectiveness in Iran: A Network Optimization Approach

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In this project, we apply network flow algorithms to evaluate the effectiveness of existing or additional sanctions for hindering the progress of Iran's nuclear program. We restrict our attention to sanctions that disrupt flows of pertinent resources to appropriate individuals or organizations. This research uses minimum cut methods to provide the key and minimum number of edges in a resource network to cut, such that the nuclear production process is impeded.

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Sanction Effectiveness in Iran: A Network Optimization Approach

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Abstract: In this project, we apply network flow algorithms to evaluate the effectiveness of existing or additional sanctions for hindering the progress of Iran's nuclear program. We restrict our attention to sanctions that disrupt flows of pertinent resources to appropriate individuals or organizations. This research uses minimum cut methods to provide the key and minimum number of edges in a resource network to cut, such that the nuclear production process is impeded.

1 INTRODUCTION

As Iran continues to bolster its nuclear program, policymakers around the world ponder their responses. Recently, the United Nations, European Union, and United States have issued several hundred sanctions to both organizations and individuals (Iran Watch, 2012). However, there is continuous disagreement as to whether these sanctions are effective in curbing Iran's nuclear arms efforts. To address global nuclear fears, it is necessary to understand the political and socioeconomic situation in Iran.

This research seeks to evaluate sanction effectiveness from a network perspective. While we do not yet have adequate data to make policy recommendations, we provide a framework for analysis of existing or additional sanctions. We plan to analyze the movement of resources pertinent to Iran's nuclear activity, such as money, raw materials, and equipment, between Iran's major political and economic entities as data becomes available. Specifically, we are interested in sanctions or alternative policy actions targeted against individuals and organizations, rather than those for purely punitive purposes. We shall refer to the movement of resources as "resource flows" for the remainder of this paper. With sufficient data, we will construct networks in which entities are connected by particular resources. We will build a separate network for each resource. For example, if the two resources under consideration were capital and missiles, we would build one network in which entities are connected by the transfer of money to one another, and an additional network in which entities are connected by the transfer of missiles to one another.

Ultimately, we propose methods to determine targeted network disruptions that can be applied to hinder the development of Iran's nuclear program. In particular, edge deletions constitute these disruptions. Here, a disruption corresponds to a sanction. This method targets key actors and relationships for termination such that resource flows are interrupted. Consequently, we can analyze the network's response via a pre-sanction and post-sanction comparison of network structure and resource flow. This analysis can be extended to multiple time-horizons, as sanctions have regularly been issued to Iran over the past five years. We restrict our attention to sanctions that disrupt flows of pertinent resources as opposed to those that are purely punitive. Thus, an intuitive metric of effectiveness is change in resource flows, specifically flow disruption. Analysis of a pre-sanction network compared to its corresponding post-sanction network would provide insight into sanction success, as our objective is preventing the movement of pertinent resources to appropriate individuals and organizations. For example, suppose a set of sanctions issued in a particular month does little to modify resource flows. Then we could safely claim that these sanctions have not been useful in hindering Iran's nuclear program.

1.1 Political and Socioeconomic Overview

In 1979, the Iranian monarchy was overthrown and Ayatollah Khomeini came to power. He was declared the "Supreme Leader," and the Iranian government was changed (CIA World Factbook, 2012). The present government consists of both elected and unelected institutions, which ultimately form executive, legislative, and judicial branches of government. A visual representation of the governmental structure can be found in Figure 1, below (BBC News). The Supreme Leader holds immense political power, whereas the President holds relatively little. The Supreme Leader, rather than the President, controls the armed forces and makes policy decisions regarding security and defense. While the President is technically elected, one must pass the vetting process of the Guardian Council in order to run for office (BBC News).

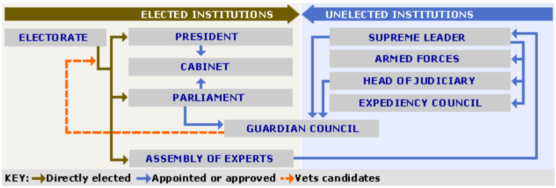

Figure 1: Diagram of the post-revolution governmental structure in Iran, courtesy of BBC News.

The dominant military force in Iran is the Islamic Revolutionary Guard Corps (IRGC)[1], a special military organization consisting of politically loyal and religiously devout personnel. The IRGC was instrumental in the success of the Iranian Revolution, and exists to this day to protect the power of the Supreme Leader from foreign or domestic threats (CIA World Factbook). It is approximately 125,000 strong and boasts its own ground, navy, and air forces. Furthermore, the IRGC manages Iran's strategic weapons. The Guards' engineering arm, Khatam-al Anbia, receives hundreds of government contracts and is believed to have billions of dollars in assets (BBC News). The IRGC also has a massive stake in numerous industries, ranging from agriculture, to vehicles, to tourism (Wehrey et .al, 2009). Finally, the IRGC receives additional funding through its control of bonyads, Iranian organizations that operate both traditional businesses as well as fund terrorist or nuclear activities. The assets of the Mostazafan bonyad alone are estimated to exceed $10 billion (Klebnikov, 2003). Thus, it is not surprising that many IRGC personnel have risen to prominent positions throughout the Iranian government. Taken together, the IRGC controls between 33%-40% of the Iranian economy (Katzman, 2006). Consequently, the organization and its leaders are points of interest when working to hinder Iranian nuclear arms production.

1.2 Sanctions Issued by the UN, EU, and US

United Nations, European Union, and United States fears of Iranian nuclear arms have caused them to issue several hundred sanctions to both individuals and organizations associated with the nuclear program (Iran Watch, 2012). However, it remains to be seen as to whether these sanctions merely harm ordinary Iranian citizens, or actually influence nuclear policy. Iran's diverse economic structure, including its numerous sectors and bonyads, allow it to avoid the worst potential sanction effects. Dr. Reza Aslan, of the Islamic Studies Department of the University of California, Riverside, believes that sanctions could prove to be counterproductive. Economic pressure on the Iranian economy would foster even greater reliance on black market activities, which are largely controlled by the Revolutionary Guards, the very organization that oversees Iran's strategic weapons. Next, insular foreign policy allows a tyrant to stay in power. Sanctions reinforce such a policy, thereby allowing the leader to consolidate his power and prevent western ideas from entering the country. Aslan contends that if Iran wants nuclear weapons, it will have them. He believes that sanctions have been entirely ineffective and that a more promising solution would be to coerce Iran into making political and economic reforms (NPR, 2010).

Similar to Aslan, Dr. Hassan Hakimian, of the London Middle East Institute, also believes that sanctions have not been, and will never be, effective in curbing Iran's nuclear efforts. He claims that Iran has expected sanctions for quite some time, allowing it to prepare for their arrival and avoid the most severe economic consequences. While sanctions exacerbate existing economic hardships in Iran, namely unemployment and inflation, such hardships only affect ordinary citizens (Wood, 2008). The elite, such as Revolutionary Guard personnel, remain unscathed. Change by internal pressure is not practical, as the IRGC would crush any efforts made by citizens to influence government policy in response to sanction hardship. Finally, Hakimian argues that sanctions may be ineffective for two reasons: false rationality assumptions and ideological beliefs. Sanctions rely upon a rational policy process in which policy-makers respond to dynamically-changing costs and benefits of a particular policy. This process is likely not rational. Next, Iran's ideologically-driven nature may allow it to tolerate sanctions for a long time (Hakimian, 2012).

In developing methods to curb Iranian nuclear arms proliferation, we seek to answer the following questions:

1. Are the sanctions currently in place effective in hindering nuclear arms production in Iran?
2. If current sanctions are ineffective, do there exist alternative, strategic sanctions that would in fact be more favorable?
3. What connections and associations must be disrupted in order to hinder nuclear arms production?
4. Given this analysis, what form of action is necessary to implement these analytical solutions?

To attack these questions, we will apply network optimization methods.

1 Also known as the Pasdaran.

2 MODEL SETUP

Network flow algorithms are part of the broader field of network optimization. Under this framework, a network is viewed as an amalgamation of routes over which a resource could traverse. A network will be constructed for each resource, e.g. funds, in which two entities are connected if the resource was transferred from one to the other. This framework allows us to analyze and track the movement of resources necessary for nuclear arms production. Nodes are classified into three types: suppliers, demanders, and intermediaries. Suppliers provide the resource to other entities within the network. They serve as points of entry for the resource. Demanders are the final recipients of the commodity. Finally, intermediaries neither ultimately send nor ultimately receive resources. Instead, they pass resources along the network. The application of network flow algorithms provides insight into which connections or entities should be disrupted in order to prevent a resource from reaching demanders. Note that arbitrarily eliminating numerous connections or entities would achieve the same result, but the solution we seek involves minimal policy intervention. Thus, if resources cannot reach their destinations, production processes cannot operate efficiently, or at peak levels. Observe that while these methods analytically determine short-term optimal policy goals, they do not inherently provide recommendations as to how these policies should be implemented or enforced.

3 DATA AND METHODS

We have requested data for this research from several international bodies. Specifically, the raw dataset requested ideally consists of material and monetary transfers, dates, and the parties involved, in relation to nuclear weapons production in Iran. Here, an entity is either an individual or an organization. A resource transfer was delineated to involve two parties: the supplying party and the receiving party.

We have created a fictitious network to demonstrate our analytical methods. Once we obtain the real dataset, we plan to construct a network in which entities are connected by a particular resource. Nodes are classified as detailed in Section 2. In classic network flows nomenclature, suppliers are sources and demanders are sinks.

Define our directed network $G = (V,E)$, where V is the node set, and E is the edge set. Note that G is directed, unweighted, and acyclic. Further, let G be one connected component. In preparation for our novel minimum cut method on a multi-source and multi-sink network, we aggregate all supplier nodes into a single "Total Supplier" node and all demander nodes into a single "Total Demander" node[2] via vertex contraction[3]. Formally, vertex contraction of nodes *a* and *b* results in a merged vertex *ab* which is "adjacent to the union of the nodes to which *a* and *b* were originally adjacent" (Weisstein, 2012). Note that *a* and *b* need not be adjacent to one another to perform this operation, as vertex contraction is a generalization of edge contraction (Weisstein, 2012). In effect, we construct all edges incident to constituent supplier and demander nodes to create the Total nodes. The algorithm presented maps the minimum cut on the aggregated network back to the original network. The proof of correctness can be found in the Appendix. Our minimum cut approach has three core steps:

1. Contract all sources and all sinks, thereby reducing the network to be single-source and single-sink.
2. Solve the reduced problem by linear programming.
3. Map the solution to the reduced problem to the original network.

We shall refer to the aggregated network as $G' = (V', E')$ for the remainder of this paper. Denote the final, aggregated adjacency matrix as matrix A. Note that the first row and column of A correspond to s, the source-node, while the last row and column of A correspond to t, the sink-node. This is no coincidence. Matrix A has been set up this way so that for the vertex set $V' = \{1, \ldots, n\}$, $1 = s$ and $n = t$ in general. These transformations allow us to apply classic maximal flow/minimum cut optimization methods, as our network now has a single source and a single sink. Since we are concerned with simply separating suppliers from demanders, these vertex contractions simplify our problem without losing any analytical detail.

Figures 2 and 3 depict the fictitious network G and its aggregated counterpart G', respectively.

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2 We use the terms "Total Supply" and "Total Demand" rather than "Aggregate Supply" and "Aggregate Demand" to avoid any ambiguity with the macroeconomic terms.

3 This transformation was performed in Microsoft Office Excel.

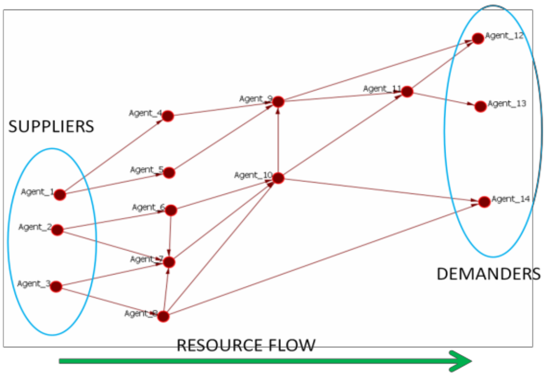

Figure 2: Original network. Supplier nodes and demander nodes are circled. Intermediaries are the other nodes. The resource flows from left to right.

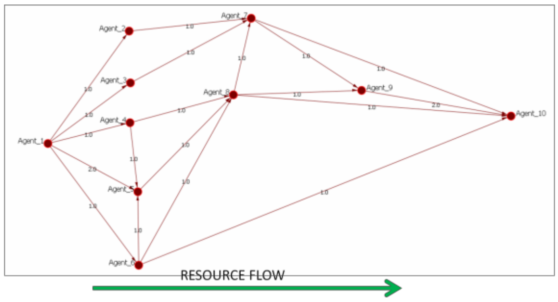

Figure 3: Aggregated network. This aggregated network *G'* has a unique supplier node *s* and a unique demander node *t*. All others are intermediaries. Node 1 is the Total Supplier and node 10 is the Total Demander. Notice that edges resulting from vertex contractions in *G* have weight greater than 1. The resource flows from left to right.

Here, entities are connected by the transfer of the resource *r* to one another. For datasets involving several resources, we would denote the network N_r as the original network for the particular resource *r*. Edges are formed in N_r based upon the existence of a resource flow, not by its magnitude. Simply stated, if a transfer is made from one entity to another, there is an edge present. A network of this form will be built for each resource of interest.

4 NETWORK OPTIMIZATION

Recall that pre-aggregation N_r is unweighted for all *r*, as it captures the flow of a given resource but not its magnitude. We apply network optimization methods in an effort to fracture the network, thereby disrupting resource flows. We disconnect the network by deleting edges, which can be equated to issuing sanctions.

The most effective network fracture separates all suppliers from all demanders because such a fracture destroys all supply chains entirely. In other words, no demander is able to receive any quantity of resource *r*. Hence, any process involving the resource *r* is brought to a halt. We apply the Ford-Fulkerson Maximal-Flow/Minimum Cut algorithm to partition the nodes into two sets *S* and *T*, where $s \in S, t \in T$ and $S,T \subset V'$. This is an S-T cut. A minimum cut is an S-T cut of minimum weight. Note that *S* and *T* must each be proper subsets of *V*. Further, $S \cap T = \{ \emptyset \}$ (Ford & Fulkerson, 1956). In our unweighted original network *G*, the weight of a cut is simply the number of constituent edges in the cut. Applied to our specific problem, a minimum cut is an S-T cut comprised of the smallest number of edges. This result follows from all capacity constraints in the original network *G* having been set to 1.

We would like to find a minimum cut for our network *G* so that resource flow is disrupted with minimal intervention on the part of policymakers such as the United Nations, European Union, and United States. The dual solution to the maximal flow problem finds exactly this, a minimum cut.

4.1 Network Flow

Given the transformations described above, we are now able to construct a resource network with a unique supplier node *s* and a unique demander node *t*. We devised and implemented our own algorithm for

transforming the aggregated adjacency matrix into a constraint matrix L and vector b, to state and solve the network optimization problem posed below:

$$\max \sum_{v:(s,v)\in E'} f(s,v) \qquad (1)$$

$$s.t.$$

$$\sum_{u:(u,v)\in E'} f(u,v) - \sum_{w:(v,w)\in E'} f(v,w) = 0 \forall v \in V' - \{s,t\}$$

$$f(u,v) \le c(u,v) \forall (u,v) \in E'$$

$$f(u,v) \ge 0 \forall (u,v) \in E'$$

where $f(\cdot)$ is the flow along an edge and $c(\cdot)$ is the capacity along an edge.

We used IBM's optimization software Cplex to solve this problem for this demonstration network, and would likewise do so for each resource network under consideration. The matrix L and vector b are imported from Microsoft Excel into Cplex. Then we solve the maximal flow problem in Cplex's OPL environment. Finally, we find the solution to the minimum cut problem by reading the dual solution.

4.2 Minimum Cut Demonstration

We have applied the minimum cut machinery discussed above to our example network, pictured in Figure 2, for demonstrative purposes. First, we solve the single-source and single-sink problem on *G'*. The minimum cut on *G'* is shown in Figure 4. The weight of a cut on *G'* corresponds to the number of edges to cut on *G*. Next, we translate the minimum cut found on *G'* to a cut on *G*, to solve the problem of interest. The method for translating the aggregated minimum cut to the decomposed minimum cut is below. While this method is novel, we do not claim it to be efficient or superior to existing multiple source/sink algorithms. We have yet to investigate our algorithm's computational complexity. The decomposed cut on the original example network is shown in Figure 5.

Before discussing the algorithm for translating an aggregated minimum cut to a decomposed minimum cut on *G*, we must introduce some terminology. An edge in *G* could have one of three possible positions: incident to two intermediary nodes, incident to an intermediary as well as a source, or incident to an intermediary as well as a sink. We shall refer to each of these edge types as an intermediary edge, supplier edge, and demander edge, respectively. Note that intermediary edges in the *E'* are guaranteed to exist in *E* because they are unaffected by the aggregation technique described in Section 3. In contrast, supplier and demander edges in the *E'* may or may not exist in *E*, as they may or may not be affected by the aggregation technique. We present the minimum cut translation algorithm below. The output of the algorithm is a vector of greater dimension than the input. This vector is a decomposition of the dual solution vector found by solving the maximum flow problem. By definition, all supplier nodes are in *S* and all demander nodes are in *T*. Note that any intermediary in set *S* or *T* of *G'* remains in set *S* or *T* of *G*, respectively. Additionally, we must decompose supplier and demander edges in the minimum cut of *G'* into their constituent edges of *E*. Thus, any constituent edges of an edge in the minimum cut of *G'* are in the minimum cut of *G*. Intermediary edges *e'* in the minimum cut of *G'* are also in the minimum cut of the *G*, as they are guaranteed to exist and therefore do not require decomposition.

We present the minimum cut translation method below. This algorithm assumes that node roles in the original network have been identified.

Recall that *G' = (V', E')*, where *V', E'* are the vertex and edge sets of the *G'*, respectively, and *|V'| = C* and *|E'| = H*. Further, let *s* and *t* denote arbitrary source and sink nodes in the original network, respectively. Also, let *s'* and *t'* be the source and sink of *G'*, respectively. Finally, let δ be the set of edges in the minimum cut of *G*.

Input: The dual solution $\hat{y} = (u_1,..., u_n, w_1,..., w_{m-1})$ [4] to the maximal flow problem solved on *G'*, matrix *D*, matrix *A*, which are the matrices corresponding to *G* and *G'* respectively.

Output: A vector $\hat{y}*$ that details the minimum cut on *G*, set *S*, set *T*, and a set of edges δ in the minimum cut for *G*. This vector $\hat{y}*$ is the dual solution to the maximum flow problem on *G*.

Below is the algorithm:

1. Define set δ.

4 In the dual solution, u_i corresponds to the *ith* flow conservation constraint. If $u_i = 0$, then node *i* is in *S*. If $u_i = 1$, then node *i* is in *T*. A value w_j corresponds to the *jth* capacity constraint. If $w_j = 1$, then edge j is in the minimum cut of *G'*. If $w_j = 0$, then edge *j* is not in the minimum cut of *G'*.

2. Scan positions 1 through $(n – 1)$ of $\hat{y}$ for components of value 1.
3. For each value of 1 detected: put the corresponding node in set T. Also put all demander nodes in set T. Put all remaining nodes in set S.
4. Scan positions $(n + 1)$ through $(n + m – 1)$ of $\hat{y}$ for values of 1 corresponding to intermediary edges. For each value of 1 detected that corresponds to an intermediary edge: put the edge in δ.
5. For any supplier edge (s', v) in the minimum cut, where s' is the Total Supplier node and v is an arbitrary node in $V'\backslash\{s,t\}$: Put all edges (s, v) in δ. These edges are located in the aggregated matrix D in any s row, column v where there is a nonzero entry.
6. For any demander edge (t', v) in the minimum cut, where t' is the Total Demander node and v is an arbitrary node in $V\backslash\{s,t\}$: Put all edges (v, t) in δ.
7. Count the number of rows in matrix D. Store this value as C.
8. Count the number of nonzero entries in matrix D. Store this value as P.
9. Compute $H := C + P$.
10. Define a vector $\hat{y}^*$ of dimension $1 \times H$.
11. For components 1 through C of $\hat{y}^*$: For any node in set T bearing j for a label[5], put a 1 in the j^{th} component of $\hat{y}^*$. Leave all other entries in components 1 through C of $\hat{y}^*$ at value 0.
12. For components $(C + 1)$ through $(C + H)$ of $\hat{y}^*$: For all edges in δ bearing k for a label[6], place a 1 in component $(C + j)$ of $\hat{y}^*$. Leave all other components in this range at value 0.
13. Output S, T, δ, $\hat{y}^*$.

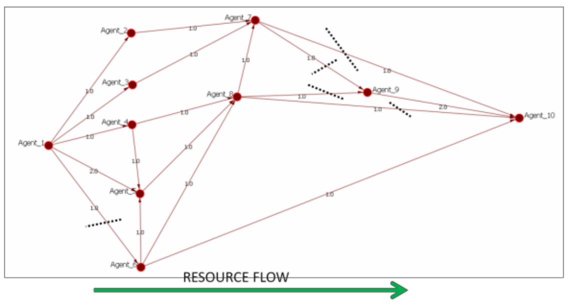

Figure 4: The minimum cut on the aggregated network. The edges in the cut are marked with a black dashed line. The capacity of this cut is 5, implying there are 5 edges to remove in G. As this is a cut, observe that there is no path from node 1 to node 10 once the cut edges are removed.

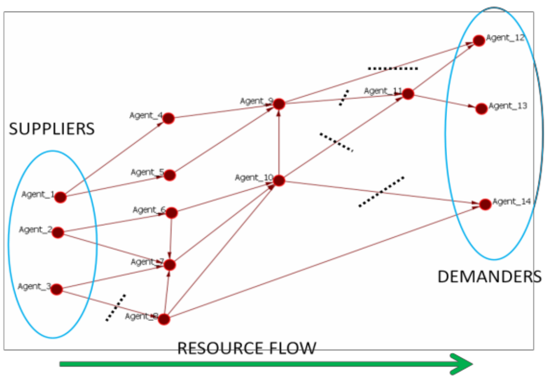

Figure 5: The minimum cut on the original network G. This cut was derived from the minimum cut found on the aggregated network. It is now clear that all suppliers have been separated from all demanders. Specifically, once the cut edges are removed, there will not exist a path in the network from any supplier to any demander, thereby bringing resource flows to a halt.

5 Any label on a node is numerical, as defined earlier in this paper.

6 The same numerical labeling scheme has been implemented as in step 3 of the constraint matrix transformation algorithm.

5 DISCUSSION

5.1 Limitations and Assumptions

While the minimum cut methods discussed above are generally independent of exact network structure, several assumptions must be satisfied in order to apply them. To apply the aforementioned methods, we require the resource network to be one connected component, and that it contains at least one supplier and one demander node.

First, the network under consideration must be one connected component, as resources cannot flow between disjoint components. In this context, a connected component corresponds to a network in which there exists a path from every supplier node to some demander node. Note that this machinery does not require the existence of a path from every node i to every node j. If our resource network N_r has q components, q minimum cuts are necessary to separate all suppliers from all demanders, since one minimum cut must be implemented for each connected component.

Next, our network must contain at least one supplier and one demander node, but not necessarily any intermediary nodes. This structural assumption stems from the resource having origins and destinations. Without both a supplier and demander node, a cut has no meaning. However, it should be noted that such a structure would generally not be found in the context explored in this research. Additionally, we do not require that the network N_r contains intermediaries because direct supplier-to-demander flows[7] are valid. The path of a resource flow could feasibly contain only one constituent edge from a supplier node to a demander node. The minimum cut methods could be readily applied to this simplified case.

In addition to the above structural requirements, we assume that flows of the resource r can actually be affected by policy action. The analysis provided is inconsequential if it is politically impractical to remove an edge from N_r. Resource flows of physical commodities are more easily cut than those of digital commodities because routes are based upon a transportation network. Transactions can be prevented by removing parts of the actual route.

Lastly, the minimum cut methods presented are novel, yet not necessarily efficient. We have not evaluated the computational complexity of the above algorithms.

5.2 Extensions

5.2.1 Multiple Resource Applications

A given nuclear arm production process typically involves numerous resource transfers, rather than just one. Yet the network optimization approach discussed examines only one resource at a time. While this serial method seems limiting, it still achieves the desired result for the general problem when applied to the ideal resource. We can determine this ideal resource, which is generally not unique, via critical path analysis (Kelley and Walker, 1959). The delay of any critical activity delays the overall project, which in this case is nuclear arms production. Hence, disrupting the resource flow necessary to completing a critical activity hinders the project.

Alternatively, a multicriteria minimum cut algorithm could be implemented to solve the problem for several resources at a time. Specifically, extensions of this research to the algorithms of Armon and Zwick's and-version of the multicriteria minimum cut problem would address the multifaceted nature of the nuclear proliferation problem.

5.2.2 Multiple Optimal Solutions

This research could also be extended to encompass multiple solutions to the minimum cut problem. The methods presented only detail one solution, inherently recommending the policy actions associated with that solution alone. However, solutions to the minimum cut problem need not be unique. In many optimization applications, uniqueness may be of little interest. But in this particular policy application, some solutions might be more easily implemented than others. For example, if there are two minimum cut solutions one might be preferred because it costs less to implement.

7 In classical network optimization nomenclature this flow would be directly from a source to a sink.

5.2.3 Insufficiency Conditions

The implementation of policies based upon the minimum cut machinery may still result in failure. That is, nuclear weapons production may only be trivially hindered even after strategic policy action is taken. If all involved parties and the resource flows between them were known, the above methods may still prove to be inadequate. Recall that after the minimum cut is applied, the vertex set V is partitioned into two sets, S and T. Theoretically, the resource r cannot move from suppliers to demanders the instant the cut is applied. However, if nodes bereft of outgoing edges in S acquire the knowledge to refine r, then the production process continues with little hindrance. We refer to using the resource to continue the production process with the phrase "refinement of the resource r." These former intermediaries have effectively become demanders, thereby allowing the next step of the production process to occur with trivial delay. In this case, resources could readily flow to these "new demanders" because the nodes in S form one connected component. One could determine how likely a former intermediary in S is to acquire the knowledge to refine r by cross-referencing the resource network with a social network involving the same entities. Closeness centrality could provide insight into the accessibility of the knowledge to each of these former intermediaries. High closeness centrality would imply that there is not much time until the former intermediary in question becomes a demander, and ultimately until the production process continues. If temporal estimates of knowledge diffusion along the social network were available, one could cross-reference closeness centralities to estimate the amount of time until further policy action is required.

If nodes bereft of incoming edges in T acquire the resource r, e.g. through black-market activities, then the production process again continues with little hindrance. Just as in S, the resource can flow freely within T because it is one connected component. Continued production processes by the demanders of the original network indicate black market activity or an incomplete resource flow dataset. Based upon the minimum cut, the resource should be unable to flow from suppliers to demanders. Hence, there must exist an unknown supplier. It is important to distinguish this situation from the previous one. If former intermediaries refine a resource, they have acquired the knowledge to do so when they lacked it before. On the other hand, if original demanders continue to refine a resource, they must have obtained it through unknown channels.

The two scenarios outlined above are cases in which implementing the minimum cut policies is insufficient to curb nuclear arms proliferation. Action beyond the minimum cut policies would be required to achieve that desired result. Thus, we refer to the two scenarios above as "insufficiency conditions." Should any one of these conditions be satisfied, the initially recommended policies would suddenly be rendered insufficient.

5.2.4 The Regime Destabilization Process

Our methods also pertain to the regime destabilization process discussed in Wood's paper (2008). If core supporters of a regime lose access to desired resources, they may cease to support that regime. Consequently, a disruption of resource flows in which supporters are demanders leads to governmental instability. In this sense, the machinery developed above can be applied indirectly to hinder Iran's nuclear development. Rather than attack the nuclear production process, implementing these network optimization methods makes for a loss of regime support. We leave the application of these methods up to the reader.

6 CONCLUSION

The construction of a network in which entities are connected by resources provides new insight into the impacts of sanctions in Iran. The model presented attempts to quantify and attribute meaning to "sanction effectiveness." The network optimization machinery discussed above could provide decision-makers with the analytical tools necessary to make informed sanction decisions. Alternatively, other policy measures could be applied to implement the analysis described. This approach would allow not only forward-looking analysis, but also historical analysis. We could apply the methods outlined to resource networks at various times. The sanctions issued could then be compared to those recommended by the minimum cut. This comparison would shed light on sanction effectiveness in earlier years.

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APPENDIX: MINIMUM CUT METHOD PROOF OF CORRECTNESS

Let $G = (V, E)$ and $G' = (V', E')$ as above. Also, let δ and δ' be the sets of edges in the minimum cut for G and G', respectively. Let $\alpha \in \delta'$ be an edge of integer weight k incident to the Total Demander node t' and some other node $j \in V, V'$. Also define a predecessor edge of a vertex j to be an incoming edge into j. Similarly, define a follower edge of a vertex j to be an outgoing edge from j.

Algorithm claim: If $\alpha \in \delta'$, then all its constituent edges $\alpha_1,...,\alpha_k \in \delta$, otherwise $\alpha_1,...,\alpha_k \notin \delta$.

Proof of correctness:
Assume $|\{e \in E \mid e = (r, j)\}| > 1$. Suppose $\alpha \in \delta'$ and there exists some $\alpha_i \in \{\alpha_1,...,\alpha_k\}$ where $\alpha_i \notin \delta$. Then in order to establish an *S-T* cut in which $s' \in S, t' \in T$, insert some predecessor edge *pred(j)* into δ. However, a partition in G has not been formed because there still exists a path from some $s \in V$ to $t \in V$ along a predecessor edge not in $\delta \cup \alpha_i$. In order to establish a partition, all predecessor edges must be in δ. Then the cut δ is not minimum. In general, there are three cases to consider regarding the in-degree and out-degree of vertex j:

Case 1: If *in-deg(j)* < *out-deg(j)*, then a cut containing α is not minimum, as a partition of can be created by a cut of smaller weight. Specifically, this partition δ contains all predecessor edges and no constituent edge of α.

Case 2: If *in-deg(j)* > *out-deg(j)*, then a cut containing all of α is minimum.

Case 3: *in-deg(j)* = *out-deg(j)*, then either a cut containing all of α or all predecessor edges is minimum. The choice does not matter, but by the argument above, a minimum cut cannot contain a combination of predecessor edges and constituent edges of α.

Similarly, by applying the arguments above and substituting follower edges of j in lieu of predecessor edges of j, if an edge $\beta \in \delta' \subset E'$, then all of its constituent edges $\beta_1,..., \beta_l \in \delta$.

QED.